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# Damping of manganese spin precession in the presence of free carriers in CdMnTe quantum wells

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**Abstract.** The transverse relaxation time $T_2$ of the Mn spins has been measured by time-resolved photo-induced Kerr rotation in n-type and p-type CdMnTe quantum wells, with a magnetic field applied parallel to the quantum well plane. The dependencies of $T_2$ on the magnetic field and on the carrier density indicate the influence of carriers on $T_2$. A model, akin to dielectric relaxation, is proposed to explain qualitatively these results.

## Introduction

Spin relaxation processes in quantum confined semiconductor structures are currently a subject of intense work. In particular, in heterostructures containing a dilute magnetic semiconductor the magnetic ions constitute a new channel for electrons and holes spin relaxation. This possibility has been considered theoretically [1] and explored experimentally through time-resolved luminescence polarization [2] and time-resolved circular dichroism [3]. Conversely, the spin dynamics of Mn ions in presence of a gas of electrons or holes has received little attention until now. Recent progress in the fabrication of modulation doped magnetic quantum wells of high quality should motivate such studies, where the opportunity to have a high density 2D gas of carriers strongly interacting with Mn spins is of primary importance. As an example K. Kavokin [4] has predicted profound changes of the Mn spin dynamics in the vicinity of the ferromagnetic transition recently observed in p-doped QWs [5].

Here we look for the influence of the electron or hole gas on the phase relaxation time of Mn spins $T_2$. The $T_2$ time was measured by time-resolved photo-induced Kerr rotation using a pump-and-probe setup. The gist of the method is to produce a rapidly varying effective magnetic field $B_{\rm eff}$, acting as a tipping pulse for the Mn magnetization M initially aligned along the external magnetic field $B_0$ $\parallel$ to the QW plane. $B_{\rm eff}$ is produced by the spin polarized carriers, mainly the holes, which are photo-created by a circularly polarized pump pulse. $B_{\rm eff}(t)$ will decay with the hole spin polarization on a time scale of a few ps, and M slightly tipped with respect to $B_0$ will continue to precess freely around $B_0$ for hundreds of ps. The component of M along the growth axis oscillates back and forth and manifests itself through the Kerr rotation of the polarization plane of the probe beam (Fig. 1).

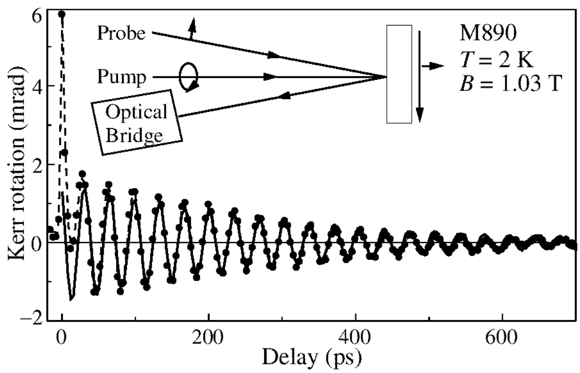


**Fig. 1.** Time-resolved Kerr rotation signal versus pump-probe delay. The signal oscillations reveal the Mn spin precession. The full line is a fit to the data with a damped sinusoid. The inset depicts the experimental geometry.

These experiments have been first proposed by Crooker et al. [6, 7], who studied ZnCdSe/ZnSe QWs containing MnSe monolayers or fraction of monolayers. Akimoto *et al.* did similar experiments on CdTe/CdMnTe heterostructures [8].

## 1 Samples and setup characteristics

We report on experiments done on two $Cd_{1-x}Mn_xTe$/CdZnMgTe QWs. One is a 80 Å width modulation doped QW of p-type with $x = 0.025$ (sample M921) and the other is a nominally undoped 50 Å QW with $x = 0.026$ (sample M890). The samples were in superfluid helium and subjected to an in-plane magnetic field up to about 1 T. Photoluminescence of the undoped QW reveals a negatively charged exciton line, an evidence that this QW contains an electron gas produced by residual donors in the barrier. The p-doped QW has a degenerate hole gas density of about $2 \times 10^{11}$ cm$^{-2}$, estimated from the Moss-Burstein shift, and could be depleted by a weak above barrier illumination.

For the pump-probe experiments we have used 1.5 ps pulses, produced at 80 Mhz by a mode-locked $Al_2O_3$:Ti laser. The polarization of the pump was modulated alternatively between left and right helicities with an Elasto-Optic Modulator (EOM) operating at 50 kHz. The pump-induced rotation of the linear polarization of the probe was detected with an optical bridge (see e.g. [7]) and a lock-in amplifier fed with the reference of the EOM.

## 2 Results and discussion

Figure 1 shows a time-resolved Kerr rotation signal obtained on sample M890. The sharp peak at short delays contains contributions from the spin-polarized photo-created carriers which relax rapidly. Measurements of the Kerr rotation at short delays allow us to deduce the spin relaxation times $\tau_e$ and $\tau_h$ of electrons and holes. The presentation of these results is beyond the scope of this paper. At delays longer than $\tau_e$ and $\tau_h$, typically a few ps or tens of ps, only the contribution from Mn persists. The full line in Fig. 1 is a fit to the experimental data with a damped sinusoid

$$S(t) = A_{\mathrm{Mn}} \exp(-t/T_2) \sin(\omega t + \phi) \tag{1}$$

where $\omega$ is the Larmor frequency of the Mn spins. In order to obtain a reasonable fit we had to introduce a dephasing parameter $\phi$, a fact already noticed in [7]. If $\omega$ were assumed

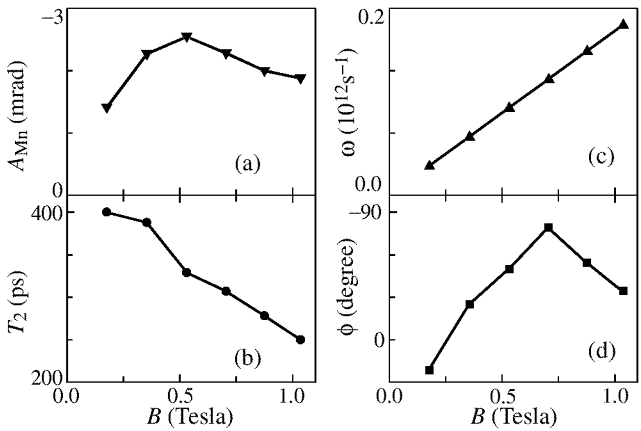


**Fig. 2.** Magnetic field dependence of the fitting parameters used in the damped sinusoid (see text) for nominally undoped sample (M890).

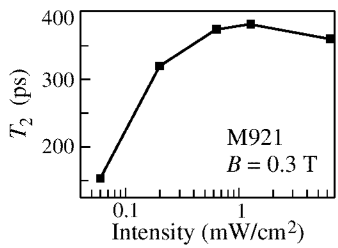


**Fig. 3.** $T_2$ versus intensity of illumination at $\lambda = 5145$ Å for the p-doped sample.

to be a constant, extrapolation back to zero would give a non-vanishing signal. Based upon this remark it was assumed in [7] that $\omega$ varies due to a time dependent demagnetizing field created by the electrons. This hypothetical field should progressively vanish as electrons recombine, producing a variation of $\omega$ during the carriers lifetime, hence a dephasing. Here we propose an alternative explanation based only on the phenomenological Bloch equations with no additional hypothesis. It can be shown that an asymmetric time dependence of $B_{\text{eff}}(t)$ in the Bloch equations leads to a non-zero dephasing given by $\tan(\phi) = -\omega\tau_h$ (mainly the holes contribute) and also predicts $A_{\text{Mn}} \propto M(\omega^2 + (1/\tau_h)^2)^{-1/2}$.

In Fig. 2 we give, for sample M890, the field dependence of the different fitting parameters which appear in Eq. (1). As expected $\omega$ increases linearly with the magnetic field (Fig. 2(c)). $A_{Mn}$ and $\phi$ follow qualitatively the behavior predicted by our model, apart the value of $\phi$ at 0.7 T which seems too large. Using $\tan(\phi) = -\omega\tau_h$ the data of Fig. 2(c–d) yield $\tau_h$ in the range 5–15 ps in agreement with the decay of the signal observed at short delays (the point at 0.7 T was excluded). The most interesting result is the marked decrease of $T_2$ with increasing field. We suggest that this effect could be related to the presence of electrons in our QW. In the case of the p-type QW the influence of holes on the $T_2$ time is readily seen in Fig. 3, and manifests itself as an increase of $T_2$ when the QW is depleted by a weak above barrier illumination.

It has been known for a long time, especially in nuclear magnetism, that free carriers may enhance the spin-lattice relaxation rate of localized spins [9]. The relaxation is basically due to a simultaneous spin-flip of the carrier and of the localized spin caused by non-

diagonal terms in the spin-spin interaction. This mechanism also contributes to $T_2$, as phase coherence is lost during a spin-flip scattering. We may estimate the efficiency of this mechanism for Mn spins 5/2 interacting with a degenerate 2D gas [10] as

$$\frac{1}{\tau_{c-\mathrm{Mn}}} = \frac{15\pi}{2\hbar}\gamma\left(\frac{\rho}{W}\right)^2 kT. \tag{2}$$

Here $\gamma$ is the carrier-Mn exchange integral, $\rho$ is the 2D density of states for one spin sub-band, $W$ is the QW width and $T$ is the carrier temperature. For electrons one finds $\tau_{e-\mathrm{Mn}} \approx 100$ ns at $T = 2$ K. The holes should be much more efficient than electrons due to the 4-fold larger exchange integral, and larger density of states. We estimate $\tau_{h-\mathrm{Mn}} \approx 3$ ns. These relaxation times are too long, even for the p-type sample, to contribute significantly to the observed $T_2$. Additionally Eq. (2) is valid only when the conduction (or valence) band spin-splitting is smaller than the Fermi energy. When this is no longer the case the spin-flip scattering should be strongly reduced, hence the relaxation time should increase, contrary to the observed decrease of $T_2$ with increasing $B_0$ (Fig. 2(b)).

We are led to propose a new relaxation mechanism, akin to dielectric relaxation, as follows. The precessing magnetization induces a spin polarization of the carrier gas. This polarization however does not establish instantaneously, but with a delay related to the spin relaxation time $\tau_c$ of the carriers. This is a source of dissipation in the course of magnetization rotation around $B_0$. The damping will be maximum, as in dielectric or paramagnetic relaxation, when the condition $\omega\tau_c = 1$ is satisfied. The corresponding relaxation time can be expressed as

$$\frac{1}{\tau^*} = \omega_c \frac{\omega\tau_c}{1 + (\omega\tau_c)^2} \tag{3}$$

where $\omega_c$ is the effective field created by the carriers on the Mn, expressed in frequency units. This model explains qualitatively our results, namely the decrease of $T_2$ with increasing field in sample M890 and with hole concentration in sample M921.

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